

Structure of regional dykes and local cone sheets in the Midhyrna-Lysuskard area, Snaefellsnes Peninsula (NW Iceland)

Alessandro Tibaldi · Fabio Luca Bonali · Federico Aligi Pasquaré · Derek Rust · Alessandro Cavallo · Alessandro D'Urso

Received: 6 April 2013 / Accepted: 18 September 2013 / Published online: 8 October 2013
© Springer-Verlag Berlin Heidelberg 2013

Abstract This paper provides the first detailed structural description of 48 vertical dykes, 384 inclined sheets and two large intrusions and the geometry (strike, dip direction and dip) of 1116 fractures in the central area of the Snaefellsnes peninsula, NW Iceland. Our data show a more complex setting than that depicted by the WNW-ESE en-echelon trend of the volcanic structures at the surface. In the Miocene basement lavas, dykes dominantly strike N50–100°E whereas other directions are also present with a higher dispersion. Two main swarms of centrally dipping sheets have also been recognized, focussing towards two areas. Sheet dips range from 2 to 75° with the higher frequency between 10 and 45°. In section view, there is no systematic variation of sheet dip with distance from the focus area. Gabbro and granophyre laccoliths are present in the studied area but cross-cutting relations indicate that most of the inclined sheets are younger. Comparison with regional tectonics suggests that the N50–80°E-striking dykes are coherent with emplacement under the stress field of the pre-6 Ma Snaefellsnes Rift dominated by a NNW-SSE-directed least principal stress (σ_3). The N80–100°E dykes and the late Quaternary WNW-trending sub-aerial volcanic features are instead consistent with the development of a more recent E-W, right-lateral shear zone

affecting the Snaefellsnes peninsula. Coherent sets of fractures have also been found. Within the inclined sheet swarms, the stress tensor rotated in response to an excess magma pressure linked to two underlying magma chambers of lobate shape, located at an estimated depth of about 400 and 500 m below sea level. This local magmatic stress also produced the centrally inclined fracture swarms that have been found in this area.

Keywords Iceland · Snaefellsnes · Dyke · Inclined sheet · Tectonics · Magma chamber

Introduction

The study of outcropping intrusive sheet swarms is of paramount importance to better understand the transport of magma in the crust, magma upwelling to the surface producing eruptions and intrusion-induced deformation. In the field these sheets can appear as complex networks of intrusions belonging to different emplacement mechanisms and events, and with diverse geometries. From reservoirs in the crust, magma commonly moves in the form of vertical, inclined or horizontal planar sheets (Acocella and Neri 2009). A vertical geometry allows upward transport of magma to feed eruptive structures at the surface or to intrude as a series of dykes (Gudmundsson 1995). Dykes or horizontal sills can allow also lateral transport of magma injected from crustal chambers (Einarsson and Brandsdottir 1980; Einarsson et al. 1997; Tentler and Temperley 2007). Dykes are normally sub-parallel to each other, occur in elongate swarms (tens to hundreds of kilometers long) (Walker 1992; 1999) and are perpendicular to the regional tectonic least principal stress (σ_3), whereas the greatest principal stress (σ_1) is vertical (Gudmundsson 1995). Dykes with a geometry controlled by tectonic stresses can thus host horizontal (lateral), vertical or

Editorial responsibility: A. Gudmundsson

A. Tibaldi (✉) · F. L. Bonali · A. Cavallo · A. D'Urso
Department of Earth and Environmental Sciences,
University of Milan-Bicocca, Milan, Italy
e-mail: alessandro.tibaldi@unimib.it

F. A. Pasquaré
Department of Theoretical and Applied Sciences,
Insubria University, Varese, Italy

D. Rust
Centre for Applied Geoscience, School of Earth and Environmental
Sciences, University of Portsmouth, Portsmouth, UK

oblique magma flow; as a consequence it is difficult to ascribe vertical dykes to the position of the source magma chambers if an extensive set of kinematic indicators is not present.

The rising of magma can also occur via inclined sheets departing at sill tips (Galland et al. 2009) or from the bifurcating of an advancing dyke giving rise to a cup-shaped intrusion (Mathieu et al. 2008) or arranged into centrally dipping swarms departing from a magma chamber (e.g. Pasquarè and Tibaldi 2007; Tibaldi and Pasquarè 2008). These swarms are considered to be the expression of magmatic stresses induced by overpressure in the magma chamber that prevail over regional tectonic stresses (Phillips 1974; Walker 1992; Gudmundsson 1998, 2002; Klausen 2004; Gudmundsson and Brenner 2005). Structural studies of centrally dipping sheets mostly focus on the geometric description of the intrusive features and their associations (e.g. Geikie 1897; Bailey et al. 1924; Schirnack et al. 1999; Klausen 2004, 2006; Pasquarè and Tibaldi 2007; Tibaldi and Pasquarè 2008; Siler and Karson 2009), sometimes combined with petrochemical analyses (e.g. Gautneb et al. 1989; Geshi 2005). Centrally dipping sheet geometry and symmetrical arrangement suggest location and depth of their magmatic source (e.g. Tibaldi et al. 2011). Uncertainties remain regarding the possibility of reconstructing the shape and exact size of the magma chamber, and further studies are necessary in order to refine the understanding of the relationships between magma chamber shape, size, depth and the different possible geometries of inclined sheets (e.g. Burchardt et al. 2011; Bistacchi et al. 2012). Recently, the origin of centrally dipping sheets has been questioned in terms of an alternative model claiming they may be linked to laterally propagating regional dykes, sourced from laterally adjacent magmatic systems, which are deflected around a central complex by stress field interference (Magee et al. 2012).

With these premises, in the present paper we wish to give an example of study of a complex network of sheets produced by multiple intrusion events and by different mechanisms, both regionally and locally controlled by stresses. Emphasis is here given to the recognition of centrally inclined sheet swarms: they are usually linked to central volcanoes (e.g. Bailey et al. 1924; Johnson et al. 1999; Schirnack et al. 1999; Ancochea et al. 2003; Klausen 2004; Geshi 2005) and thus the recognition and study of these sheets is useful in understanding the behaviour of volcanic systems and the interpretation of modern geophysical signals for volcanic hazard assessment. The systematic analysis of centrally inclined sheets, as illustrated in the present work, is a relatively new topic of research and more data are necessary in order to improve understanding of sub-volcanic plumbing systems. In fact, outcrops of centrally inclined sheet swarms below eroded volcanoes are usually limited in lateral/vertical extent, with different geometries of inclined sheets being found, as well as different numerical models proposed to explain these phenomena. These models comprise: (1) concave-downward (trumpet-shaped) sheets with increasing dip closer to the

magmatic source (Fig. 1a) (Phillips 1974); sheets are missing in the central part and are associated with calderas and decreasing magma pressure. (2) Concave-upward (bowl-shaped) sheets with decreasing sheet dip with depth from a pressurised magma chamber below a caldera (Fig. 1b) (Phillips 1974); sheets are missing in the central part. (3) Radial planar sheets from a spherical magma chamber (Fig. 1c) (after Chadwick and Dieterich 1995; Gudmundsson 1998). (4) Planar parallel to sub-parallel sheets originated from a lobate (sill-like) magma chamber (Fig. 1d) (Gudmundsson 1998; Schirnack et al. 1999; Tibaldi et al. 2011; Bistacchi et al. 2012).

The principal aim of this paper is thus to provide a detailed description of the geological and structural features of the intrusive sheets present in the Midhyrna-Lysuskard area, Snaefellsnes Peninsula (NW Iceland, Fig. 2), where vertical dykes, inclined sheet swarms and laccolith bodies are present (Upton and Wright 1961; Gianelli 1972). The purpose is to unravel the emplacement history of these previously little studied intrusions and to decipher which might be linked to regional phenomena, and which to local magma sources. Structural data consist of GPS located strike, dip direction, dip and thickness of 48 vertical dykes, 384 inclined sheets and two large intrusions and the geometry (strike, dip direction and dip) of 1,116 fractures. Some of these intrusions have also been sampled at key sites and analysed from a petro-chemical point of view. Emphasis has also been placed on the evaluation of uncertainties regarding the location of the magma source for the centrally inclined sheets.

Iceland is an ideal natural laboratory for collecting field data on shallow magma feeding systems: tectonic uplift and glacial erosion of Tertiary–Quaternary magmatic complexes exposed several intrusive sub-volcanic bodies (e.g. Walker 1958, 1960, 1974, 1975; Bald et al. 1971; Fridleifsson 1977; Gautneb et al. 1989; Gudmundsson 1990, 1995, 2002; Klausen 2004, 2006; Paquet et al. 2007; Tibaldi and Pasquarè 2008; Siler and Karson 2009; Burchardt et al. 2011). Moreover, useful data can be collected to analyse regional dykes and their connection with remote tectonic stresses, and local intrusive sheets linked to local magmatic forces (e.g. Gautneb and Gudmundsson 1992; Gudmundsson 1998, 2006; Geshi 2005; Pasquarè and Tibaldi 2007; Tibaldi and Pasquarè 2008).

Geological and tectonic framework

The Icelandic crust has been constructed by the combination of hot spot and mid-ocean ridge magmatism (Schilling 1973; Gudmundsson 2000; Jacoby and Gudmundsson 2007; Einarsson 2008; Jakobsdóttir et al. 2008; Mjelde et al. 2008). Its geological framework displays basalts of Tertiary age that flank the presently active rift system that runs through the island from SW to NNE. The 80-km-long and 10 to 30-km-wide Snaefellsnes Peninsula hosts three volcanic systems that form the Snaefellsnes Volcanic Zone (SNVZ): (1) The

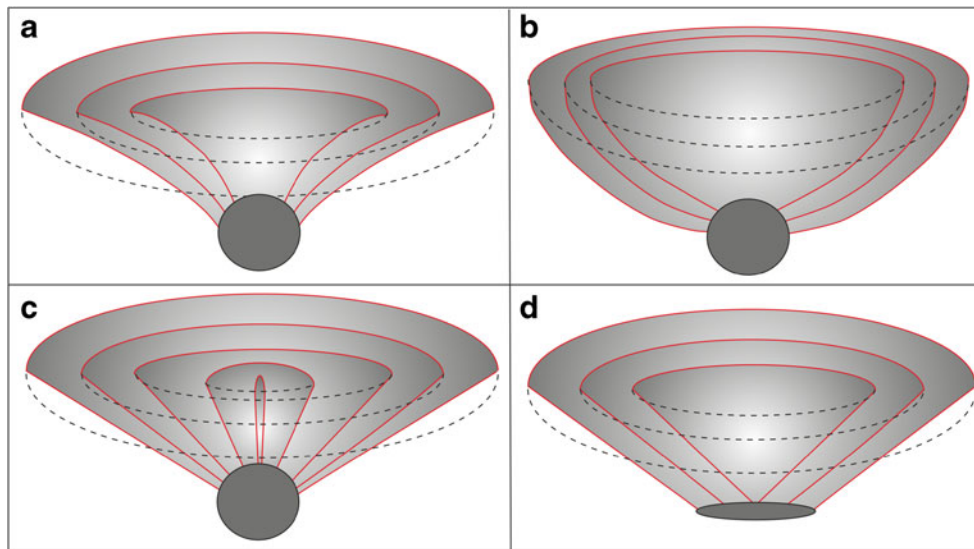


Fig. 1 Possible geometries of centrally inclined sheet swarms resulting from internal excess magma pressure: **a** radial planar sheets from a spherical magma chamber (after Chadwick and Dieterich 1995; Gudmundsson 1998); **b** concave-upward (bowl-shaped) sheets from a spherical magma chamber (after Chadwick and Dieterich 1995;

Gudmundsson 1998); **c** concave-downward (trumpet-shaped) sheets from a sill-shaped magma chamber (after Phillips 1974; Chadwick and Dieterich 1995); **d** planar parallel sheets from a laccolith-like chamber (after Schimick et al. 1999; Bistacchi et al. 2012)

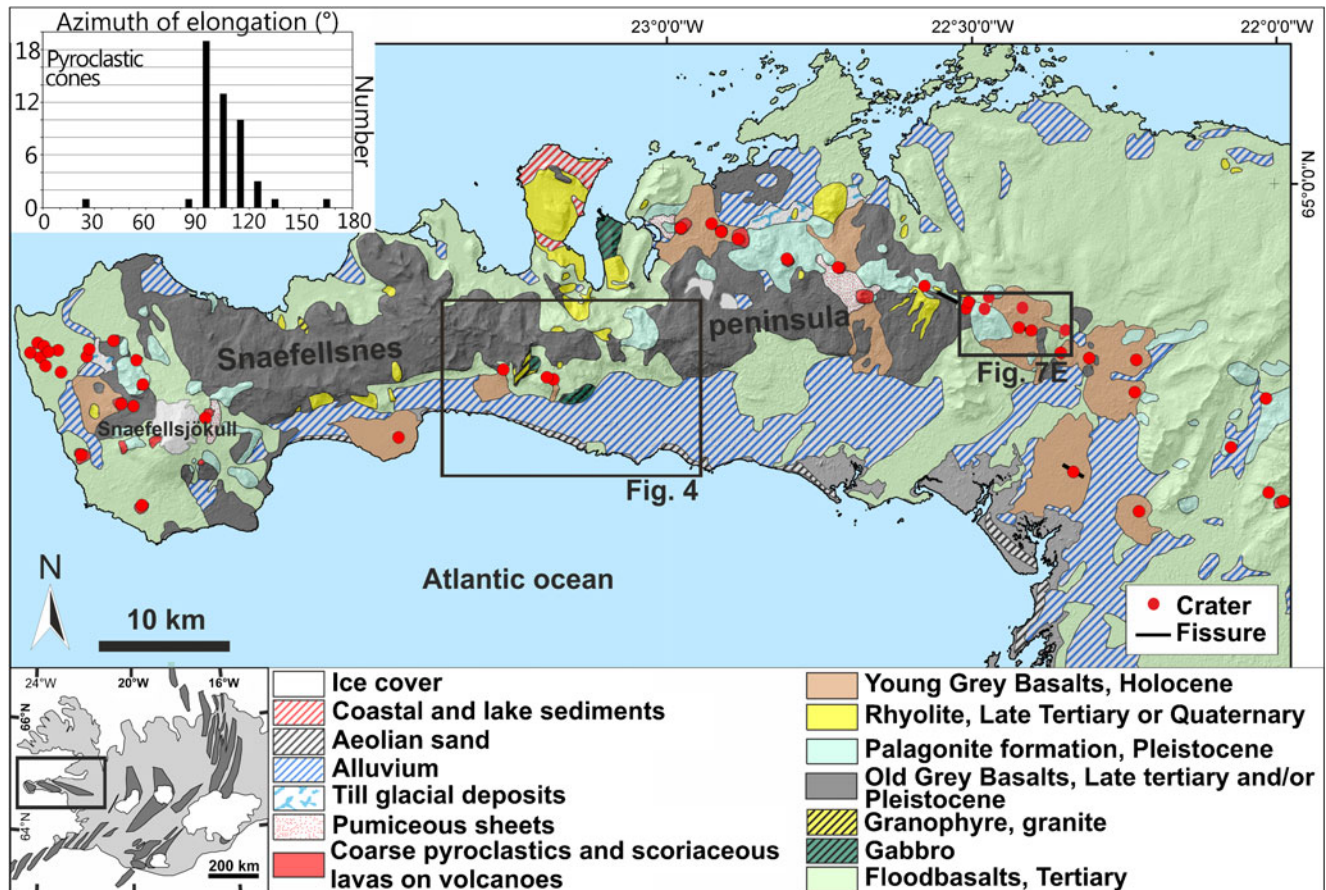


Fig. 2 Regional geological framework of the study area. *Inset* shows Iceland with rift zones. Modified after Kjartansson (1968). *Rectangle* location of the study area. The graph shows the azimuth distribution of elongation direction of the pyroclastic cone base and craters

central stratovolcano Snæfellsjökull, located on the westernmost tip of the peninsula (Fig. 2), whose latest activity has been dated to 1750 BP by Steinthorsson (1967); (2) the Lýsuhóll volcanic system, located further to the East and active during the Holocene and (3) the Ljósufjöll volcanic centre, the easternmost of the three systems of the SNVZ, the latest eruptive activity of which dates back to 960 AD (Flude et al. 2008). Sigurdsson (1970) highlighted the occurrence of WNW-ESE-trending, en-echelon alignments of pyroclastic cones and vents along the SNVZ, and attributed this volcano-tectonic arrangement to the activity of a right-lateral, E-W-striking shear zone affecting the Snaefellsnes peninsula and most likely produced by differential spreading rates in North and South Iceland in late Pleistocene times. The study of the SNVZ is of paramount importance also because it is characterized by a markedly different trend in comparison to all the other volcanic zones in Iceland.

The peninsula is composed (Fig. 2) of basaltic lavas and palagonites ranging in age from late Tertiary to Holocene. Along the northern side of the peninsula rhyolites also occur. Glacial erosion and dissection have revealed three magmatic complexes: the Midhyrna and Lysuskard intrusions on the southern side of the peninsula, and the Kolgrafarmúli intrusion on the northern side, all of them intruding the Tertiary basalts (Fig. 2). The southern intrusions, located in our study area, were first investigated by Upton and Wright (1961) and Gianelli (1972). The former authors identified a distinctive layered texture for the Midhyrna intrusion, represented by alternating layers of mesocratic and leucocratic gabbro. With regard to the Lysuskard body, a composite intrusion of gabbro and granophyre, they suggest an earlier phase with the intrusion of quartz-gabbro, followed by the intrusion of granophyric magma. Chilling of granophyre against gabbro, observed in the field by Sigurdsson (1970), as well as our observation of granophyric veinlets cross-cutting the gabbro would confirm the above scenario. Absolute age determinations for the granophyric body indicate a range of 1 to 2 Ma (Welke et al. 1968), whereas the gabbroic intrusion was dated at 1.1 Ma (Moorbath et al. 1968). Since structural evidence suggests that the granophyric body postdates the gabbro, we assume 1 Ma as the most reliable age for the former.

Field data

The study area is located in the south-central portion of the Snaefells peninsula (Fig. 3). Our systematic mapping of lithostratigraphic units and structures (at a 1:10,000 scale), enabled us to shed light into the local stratigraphy and geometry of magmatic intrusions and fracture systems. Dykes and sheets, particularly well exposed along rivers and gullies in the study area, were measured and mapped at several structural stations. Dykes have been distinguished from inclined sheets based on their dip angle. Taking into account the general

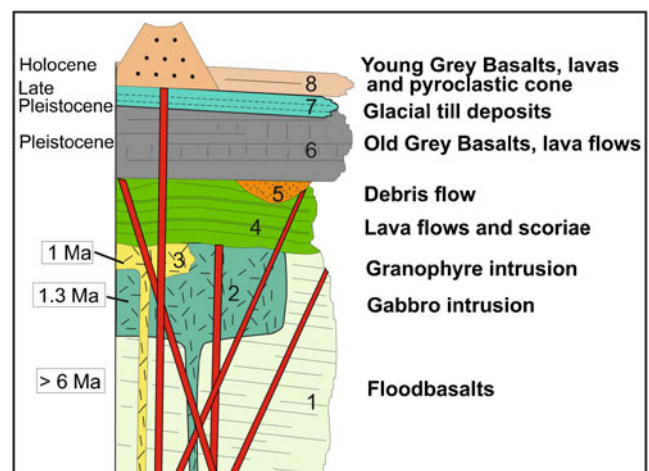


Fig. 3 Stratigraphical column showing all the units cropping out in the study area, as well as their emplacement relationships (based on an original 1:10,000 scale field survey by the authors)

attitude of the older part of the lava succession that shows a slight tilting, and thus the older dykes can have suffered a comparable dip decrease, we considered a discriminating dip value at 65° . Anyway it must be noted that most of the dykes have dip angle $>80^\circ$ and only four have dip angles of $66\text{--}75^\circ$. Thus even if these four sheets might belong to the centrally inclined sheet population, the results and interpretations of this paper would not be affected. Cross-cutting relationships between the various intrusions and with the lithostratigraphic units were studied, with the purpose of defining the succession of emplacement events. Rock samples were collected and analysed by optical microscopy on thin sections and preliminary whole-rock geochemistry. Some of these results are briefly provided below; more thorough details are outside the scope of the present work and will be presented elsewhere. Finally, fractures (not related to magma cooling or to local surface gravity effects) were identified and measured to analyse the brittle deformation in the area. Non-cooling fractures were distinguished by considering only those cutting more than one depositional unit, and only fractures not parallel to the local slope have been measured to avoid gravity-induced structures. Most fractures are master (i.e. long) joints and hence it was almost always impossible to reconstruct their kinematics. In a few cases extensional (mode I—opening) deformation has been recognized but this was not statistically significant.

Geological mapping

The mapped lithostratigraphic succession in the studied area is represented by a series of lava flows, large laccoliths and Holocene cover rocks and sediments (Fig. 3). At the base of the exposed succession are dark grey basaltic lava flows of Tertiary age; single flows are 1 m to a few meters thick, with a general gentle dip to the east. This unit is characterized by a

fine-grained microcrystalline to aphanitic texture, display clear alteration features, are mostly massive and rarely brecciated. They are intruded by the Midhyma-Lysuskard gabbros, characterized by massive basic rocks with millimetric to centimetric crystals of plagioclase, clinopyroxene, olivine and smaller amounts of amphibole, biotite and Fe-Ti ore. The Midhyma gabbro, located in the eastern part of the study area, locally shows a clear magmatic layering dipping 15–17° to the north. The contacts with the host rocks are clear and sub-vertical. In the western part of the study area the Lysuskard composite intrusion is made up of a gabbroic body intruded by a major body of massive granophyre, and secondary smaller leucocratic intrusions.

An unconformity marks the contact with the overlying succession, which, at the base in the western part, is composed of dark, thin lava flows (thickness of single flow units generally in the order of 1–2 m) interlayered with autoclastic breccias (thickness < 1 m). The eastern part is overlain by a lens-shaped deposit rich in angular volcanic centimetric–decimetric fragments embedded in a millimetric matrix, orange in colour, which can be interpreted as a volcano-clastic flow filling a palaeovalley. These deposits are in turn overlain by massive, light grey, up to 10-m-thick lava flows, which show characteristically pervasive columnar jointing. The uppermost flow shows evidence of glacial erosion and thus the succession between the unconformity and this flow has an age between 1.1 Ma and the last glacial period, consistent with the regional unconformity of Snaefellsnes between the Tertiary lava pile and the Plio-Pleistocene sequence (Sigmundsson and Schmundsson 2008). Above are glacial deposits belonging to the Last Glacial Maximum and Holocene dark lava flows erupted from pyroclastic cones and fissures.

The basal Tertiary lava flows and the gabbroic and granophyric intrusions are cut by most of the inclined sheets and vertical dykes that do not intrude the overlying succession. Some inclined sheets and one vertical dyke have been observed to depart from the Lysuskard granophyre, whereas one dyke has been seen to intrude the younger units.

Dykes and inclined sheets

In the mapped area we measured 48 dykes (dip angle $\geq 66^\circ$; Fig. 4) that cut the older rock succession of Tertiary age; a few cut the gabbroic laccolith and the 1-Ma-old granophyric body as well, and one the Pleistocene lava flows of Unit 6 (Fig. 3). Most of the dykes strike between N50°E and N100°E, whereas other attitudes are widely scattered (Fig. 5a). The average thickness of dykes is 0.85 m. No correlation has been found between dyke dip and thickness (Fig. 5b). Some intrusions propagated from the massive granophyre; they are mostly represented by veins and in one case a meter-thick dyke.

We also identified and measured 384 inclined sheets (dip angle $\leq 65^\circ$) that cut all the rocks up to the base of the debris

flow (Unit 5) and of the Pleistocene lava flow, Unit 6 (Fig. 3). At regularly spaced intervals each sheet was measured, in terms of its dip direction and dip, in order to precisely reconstruct its geometry. Each sheet was also described in terms of thickness, measured at intervals of ~5 m along each exposure; the average figure was then recorded as the most representative. With regard to the attitude of the sheets, almost all dip directions are represented, apart from the range N150–210°E, with a peak corresponding to sheets dipping towards the NW (Fig. 5c). The absence of south-dipping sheets will be discussed in the following section. As was the case for dykes, no correlation has been found between sheet dip and thickness (Fig. 5d). The thickness range of individual swarms in Iceland is between 0.1 and 1 m (Gudmundsson et al. 1996). The average sheet thickness in our sheet population is 0.63 m, whereas the cumulative thickness of all the 384 sheets is 240.7 m. We then calculated the cumulative thickness of the sheets ranging in strike from N50°E to N130°E, corresponding to the strike range of dykes in the area parallel to the rift. The obtained value of 64.28 m, has enabled us, as illustrated in the following section, to show a clear difference between the studied sheet swarms and the Ardnamurchan cone sheet swarm (and related emplacement model) described by Magee et al. (2012).

A W-E panoramic view (Fig. 5e) of most of the study area shows that inclined sheets in the western sector dip towards the E, whereas in the central area there is the intersection of two different sheet swarms (Fig. 6) since they dip both towards the W and E. In the eastern zone (not included in Fig. 5e), the sheets dip preferentially to the W. The average sheet dip of our entire population is 28°, lower than other sheet swarms in Iceland whose average dip is 34° (Gudmundsson et al. 1996). A plot of sheet dip versus distance from the centre of the two swarms, shows no definite pattern of decrease or increase, corresponding to similar situations found elsewhere (e.g. Tibaldi et al. 2011). It can be noted, however, that as far as 5 km from the centre of each swarm sheet dips range from a few degrees to 65°. Beyond 5 km from the centre of each swarm dips become shallower, ranging between a few degrees and 50°.

We plotted (Fig. 6) the dip direction for each of the sheet localities and obtained clusters of poles to planes; these clusters are perpendicular to the most frequent dip direction that can be called “sheet trajectory” as it is tangential to the depth trajectory of the intrusions (Klausen 2004). The “sheet trajectories” are shown as arrows, and it can be observed that they converge towards two focal areas, distinguishing two different inclined sheet swarms, a western one (blue arrows) and an eastern one (black arrows). The sheets belonging to the two swarms are labelled I and II, respectively, in Fig. 7. Although few dykes are present within the area corresponding to the centrally dipping sheet swarms, in a few instances it has been possible to observe cross-cutting relationships between dykes and inclined sheets: in the easternmost part of the study area, a

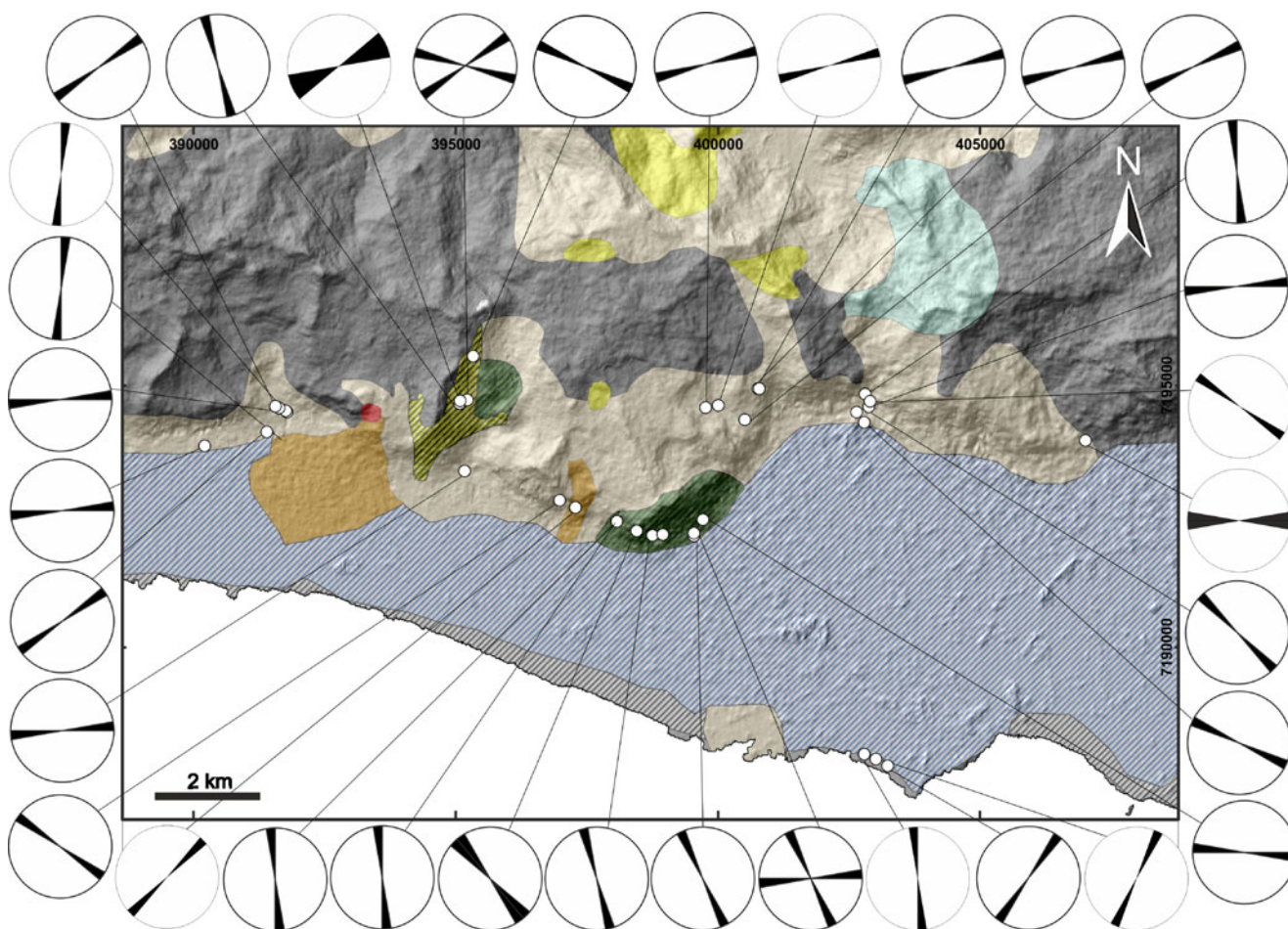


Fig. 4 DEM of the study area with rose diagrams depicting dyke strikes. *White dots* indicate measurement sites

N75°E-striking dyke cuts an eastward-dipping inclined sheet (Fig. 7a); at few other sites throughout the study area, dykes striking from N75°E to N85°E cut sheets with different dip directions. At two sites, E-W striking dykes are cut by NNE- and NNW-dipping sheets. It has also been possible to document, in a few instances, cross-cutting relationships between sheets with different attitudes (Fig. 7b and c), with the sheets belonging to swarm II (the eastern one) cutting the sheets belonging to swarm I (the western one).

Fractures

We measured 1,116 fracture planes that can be grouped into different sets, with steep dips (>70°), as well as low angles (mostly <45°; Fig. 8). The most frequent vertical fractures systematically strike about E-W in 19 out of 29 sites of measurement. In the remaining ten sites, vertical fractures strike mostly WNW-ESE. To a lesser extent, WSW-ENE and N-S-striking vertical fractures are also present, in decreasing order of frequency.

Shallow-dipping fractures are present at all measurement sites apart from one, and they tend to decrease or disappear

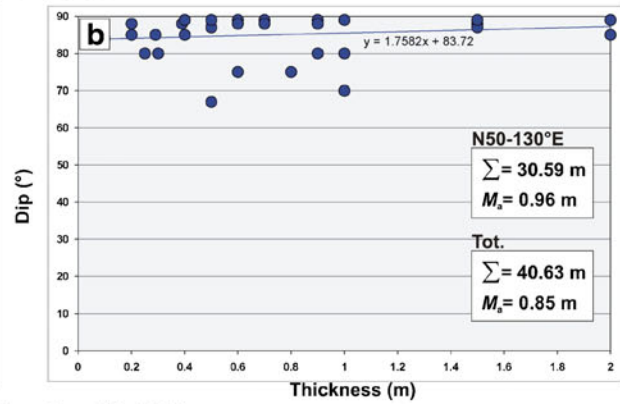
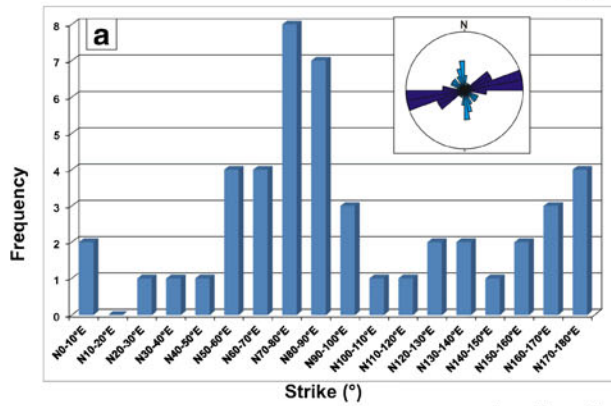
towards the borders of the area represented in Fig. 8. They show a tendency to dip towards the focal areas of the two centrally inclined sheet swarms, although at some sites the situation is more complex, with a few other fracture sets observed.

Holocene volcanic features

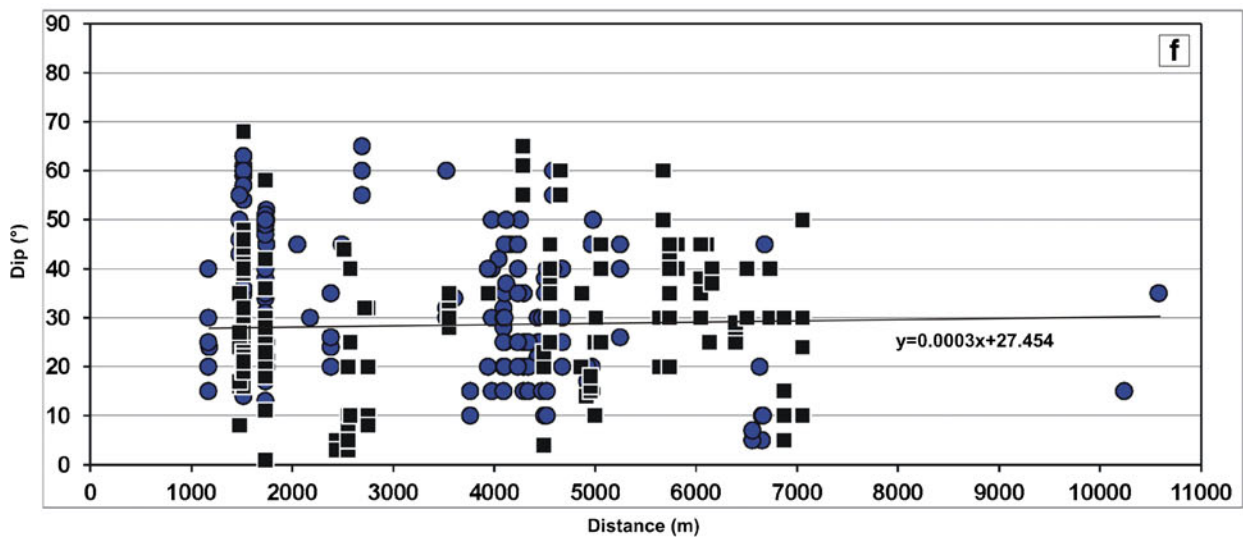
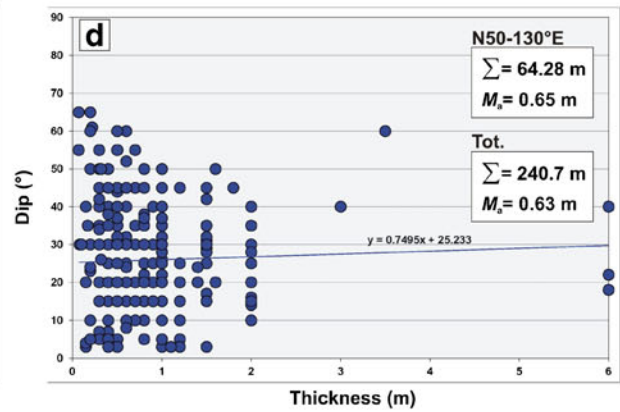
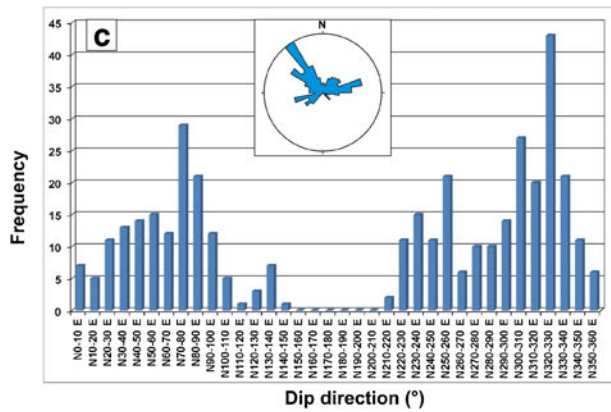
In order to reconstruct the most probable orientation of the Holocene dykes near the surface, we analysed the alignment of Holocene volcanic features all along the Snæfellsness Peninsula as well as the morphometric characteristics of single

Fig. 5 General graphs of the measured intrusive sheets. Vertical dykes: **a** number (*Y*-axis) vs. dip direction (*X*-axis); **b** dip (*Y*-axis) vs. thickness (*X*-axis), the *inset* numbers represent the cumulated total thickness and average thickness (above only for dykes N50–110°E, below all dykes). Inclined sheets: **c** number (*Y*-axis) vs. dip direction (*X*-axis); **d** dip (*Y*-axis) vs. thickness (*X*-axis), the *inset numbers* represent the cumulated total thickness and average thickness for sheets striking N50–130°E (*above*) and for all sheets (*below*); **e** photo of the central part of the studied area where the inclined sheets of the two swarms intersect. **f** Dip (*Y*-axis) vs. distance from the focal area of the centrally inclined sheet swarms

Dykes - N. 48



Inclined sheets - N. 384



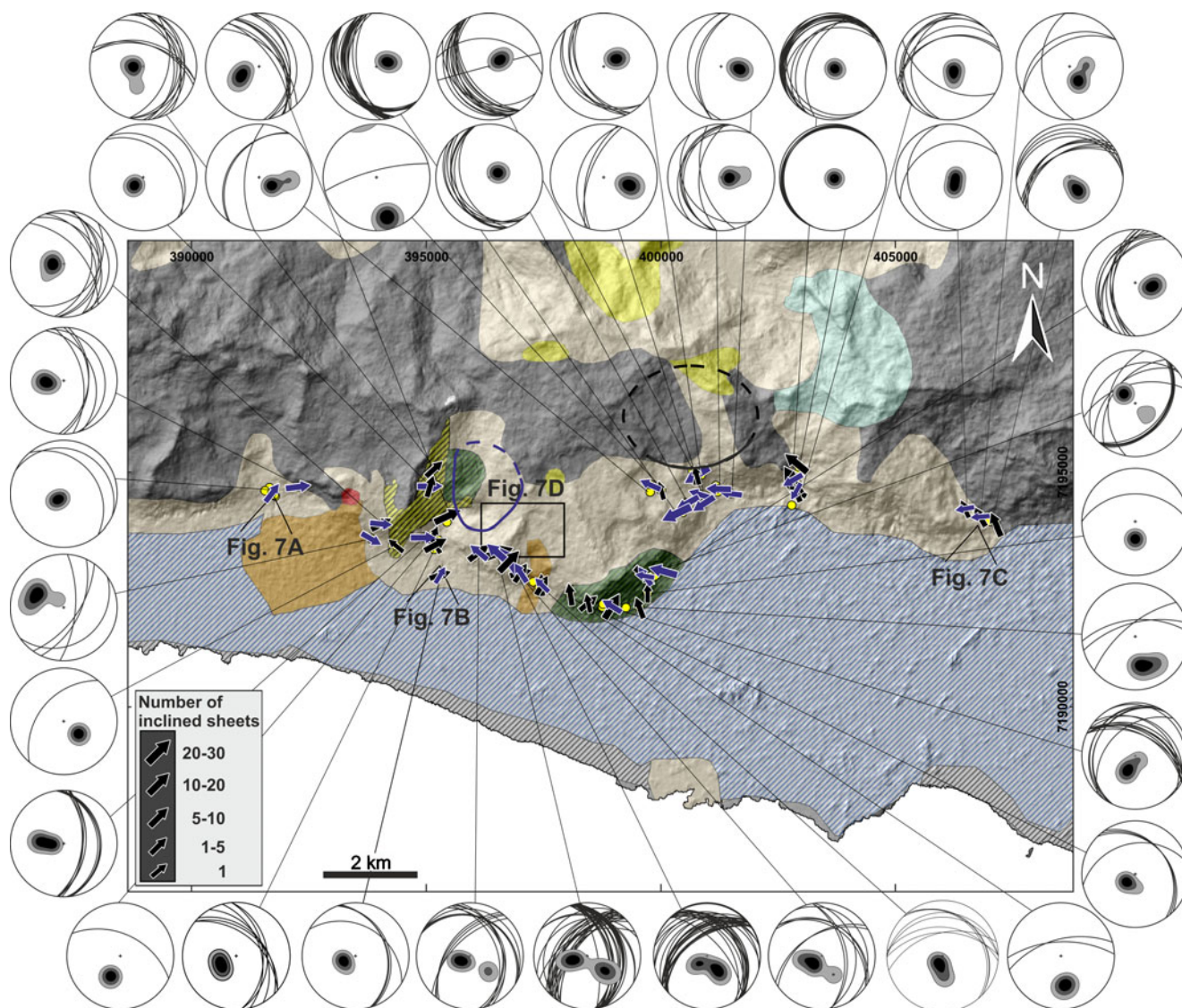


Fig. 6 DEM of the study area with stereograms (Schmidt's projection, lower hemisphere) of the inclined sheets and related poles to planes. Arrows point to the average dip direction at each site of measurement

of homogeneous populations, highlighting the center of each inclined-sheet swarm with *blue arrows and blue circle* referring to the western center, and *black arrows and black circle* to the eastern center

Holocene vents and pyroclastic cones (e.g. Fig. 7e). This is based on works suggesting that the most detailed geometric definition of the near-surface magma paths can be determined by combining a series of morphometric parameters of main craters and monogenic volcanic edifices with fissure eruption orientation (Tibaldi 1995; Corazzato and Tibaldi 2006; Bonali et al. 2011). Applying these criteria, the reconstruction of the azimuth of the near-surface Holocene magma pathways was based on: (1) alignment of closely spaced vents, (2) alignment of nested craters, (3) elongation of crater, (4) elongation of pyroclastic cone base and (5) trend of eruptive fissures.

We analysed a total of 51 pyroclastic cones and craters, 90 % of which are elliptical in plan view. These data indicate the dominance of volcanic features trending N90–120°E (graph in Fig. 2), with a few other scattered azimuths.

Pyroclastic cones and vents are mostly N90–110°E aligned, resembling the dominant trend of elongated craters and cone bases. As a whole, they depict a series of WNW-oriented volcanic chains with an en-echelon geometry in plan view, in agreement with Sigurdsson (1970).

Petrography and geochemistry

Preliminary mineralogical and geochemical investigations were carried out on 24 rock samples (sheets, dykes and plutonites) using polarized light microscopy on thin sections, energy-dispersive X-ray fluorescence (EDXRF, Panalytical Epsilon 3, major elements) and X-ray powder diffraction (XRPD, PANalytical X'Pert PRO PW3040/60 diffractometer in θ - θ Bragg-Brentano parafocussing geometry). EDXRF

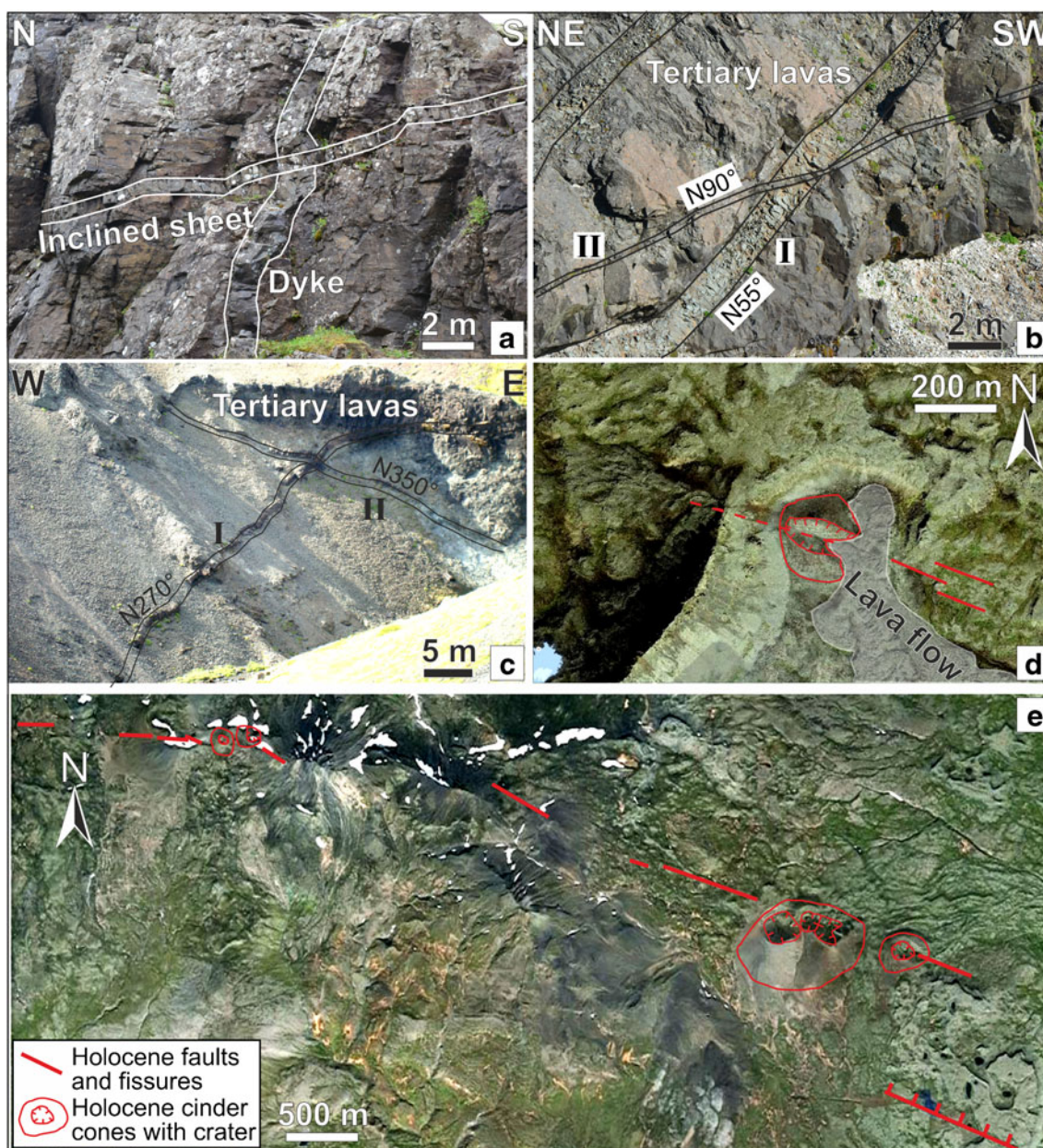


Fig. 7 Field example of cross-cutting relationships between inclined sheets and E-W vertical regional dykes (a), and between inclined sheets (b and c). Note that the sheets belonging to the eastern centrally inclined sheet swarm (II) offset the sheets of the western swarm (I). d and e show

WNW-elongated and aligned Holocene pyroclastic cones and WNW-striking fractures respectively in the field studied area and in the eastern Snaefellsnes Peninsula (for location see Figs. 2 and 6a)

results suggest that analysed samples could be classified into the alkaline series (Fig. 9a). The Midhyrna gabbros display a widespread compositional layering and cumulus microstructure, and they are constituted mainly by plagioclase (with marked normal or oscillatory zoning) and ophitic clinopyroxene, with smaller amounts of olivine, orthopyroxene, hornblende, biotite and quartz. Typical accessory minerals are apatite, magnetite, hematite and ilmenite; secondary minerals like chlorite, calcite, epidote and zeolites are quite common, especially where hydrothermal alteration occurred. The Lysuskard valley intrusives have a quite heterogeneous composition, ranging from

granophyres to “hybrid” diorites and gabbros: the magmatic contacts are highly irregular, with extensive veining and brecciation. The granophyres are composed mainly of quartz and K-feldspar (perthitic orthoclase) intergrown in granophyric aggregates, with smaller amounts of albite, chloritized biotite and hornblende. The diorites contain plagioclase (with marked zoning), clinopyroxene (augite), hornblende, biotite, quartz, minor K-feldspar and Fe-Ti oxides; the gabbros consist mainly of zoned plagioclase, idiomorphic clinopyroxene (augite) with smaller amounts of quartz and accessory minerals (apatite, Fe-Ti oxides). Sheets and dykes are generally holocrystalline under

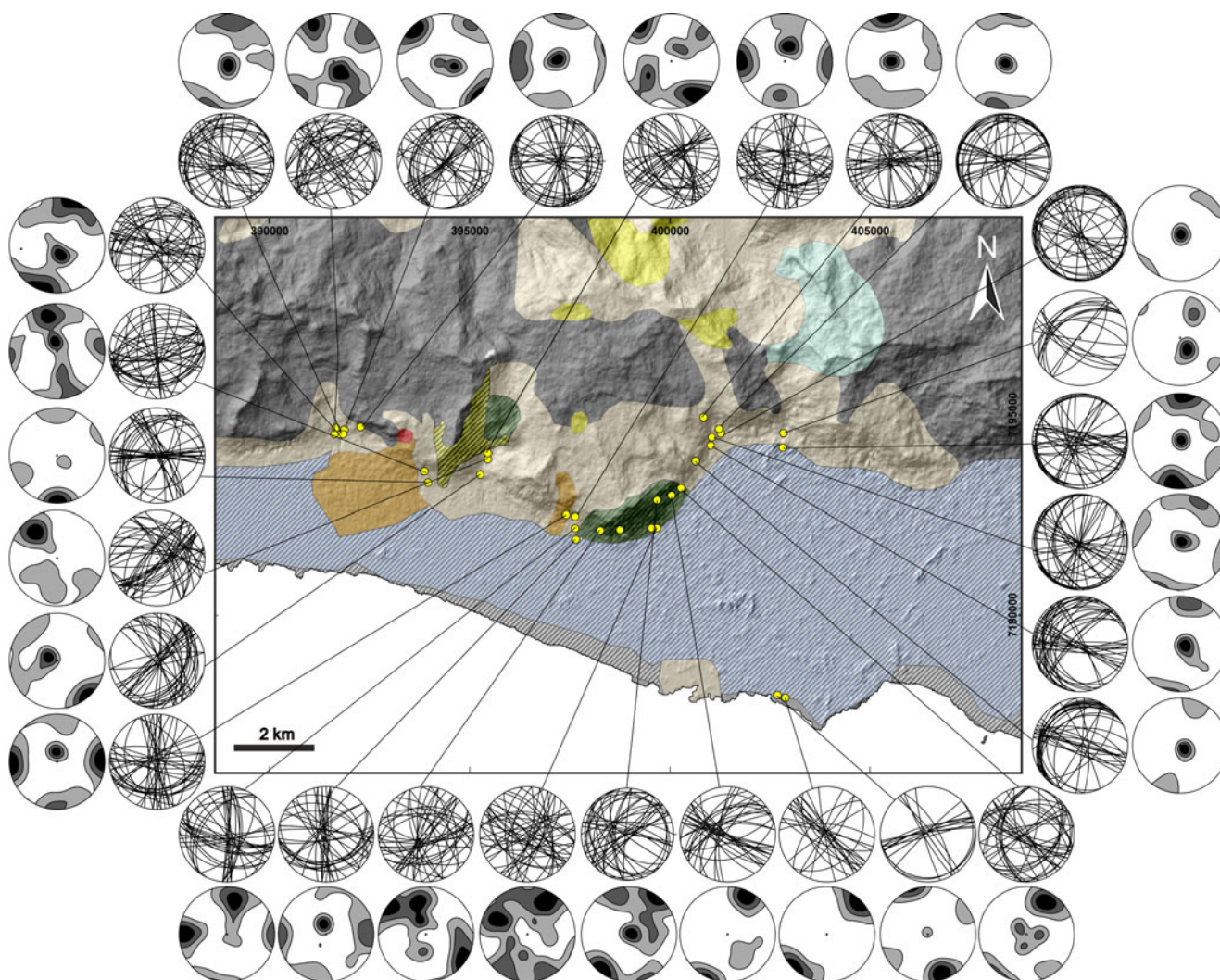


Fig. 8 DEM of the study area with stereograms (Schmidt's, lower hemisphere) of the measured fracture planes and of their poles

the microscope, with a varied content of small phenocrysts surrounded by a fine-grained groundmass; their composition ranges from basic-ultrabasic up to granophyric, like the corresponding plutonic rocks. Hydrothermal alteration and secondary minerals like calcite, chlorite and zeolites are quite common, especially close to the intrusive contacts. More acid dykes are located in correspondence of the large granophyric body, whereas basaltic dykes are widespread in the surrounding areas (Fig. 9b). Similarly, more acid inclined sheets point towards the Lysuskard granophyric body, whereas basaltic inclined sheets point towards different directions.

Discussion

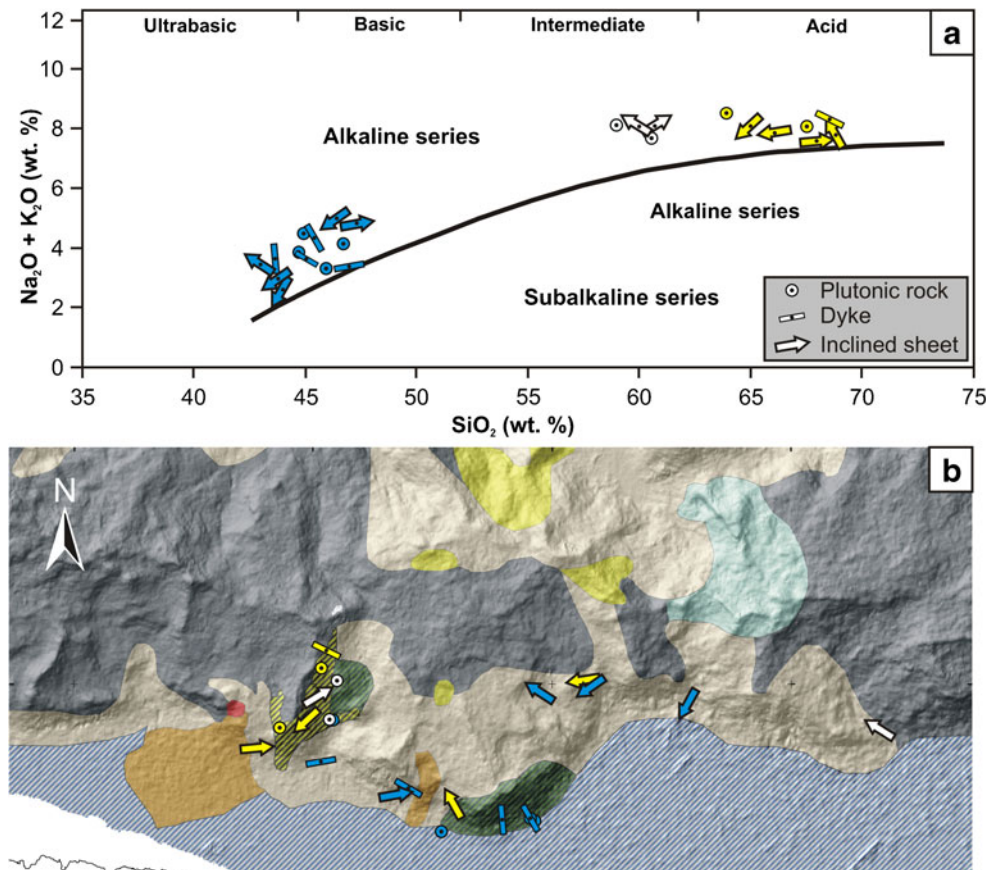
Dykes

In the Midhyrna-Lysuskard area we found 48 vertical to sub-vertical dykes. Most dykes strike N50–100°E, while other

orientations are more dispersed. They cut the older rock succession of Tertiary age and a few of them also the gabbro laccoliths and the large 1-Ma-old granophyric body. In one case a dyke cuts all the complete Pleistocene succession of lava flows (Fig. 3). Locally, it has also been possible to observe that some E-W-striking dykes cut the centrally inclined sheets, whereas other dykes are cut by inclined sheets, suggesting that dyke intrusion occurred both pre- and post-inclined sheets. For the younger volcanic structural features of Holocene age, we observed that the strike of the magma feeding paths at the surface, obtained from the orientation of eruptive fissures and from the morphometric characteristics of the pyroclastic cones of the Snaefellsness peninsula, are in the range N90–120°E.

In comparing these data with regional structures, it must be borne in mind that the SVZ is made of three main volcanic systems trending WNW-ESE with an en-echelon arrangement (Sigurdsson 1970). In the centre, corresponding to our area of study, the Ljosufjoll system is the largest and has been active

Fig. 9 **a** Chemical classification of the Midhyrna and Lysuskard rocks (intrusives, dykes and sheets), using the total alkalis versus silica diagram of Cox et al. (1979) adapted by Wilson (1989) for plutonic rocks. Circles laccoliths, arrows inclined sheets, lines dykes. The strike and dip direction is shown for dykes and sheets, respectively. Each segment symbol is oriented as the dyke from which the sample has been taken; each arrow points as the dip of the corresponding sampled inclined sheet. **b** Location of the intrusions analysed in (a), showing again the original orientation



for the last 0.7 Ma (Thordarson and Hoskuldsson 2002). During the Holocene, its volcanic activity stretched across most of the peninsula, totalling 23 basaltic eruptions in the last 10 Ky (Thordarson and Hoskuldsson 2002). The location of the Quaternary SVZ corresponds to the E-trending Tertiary Snaefellsnes syncline, known as an ancient rift zone actively spreading until 6–7 Ma ago when the plate boundary shifted to its present position in the West Iceland volcanic rift, followed by rejuvenation of volcanism at 1.1 Ma (Jóhannesson 1980; Kristjánsson and Jonsson 1998; Martin and Sigmarsson 2010). These data suggest that the dominant N50–100°E strike of the measured dykes is only in part consistent with the geometry of the regional volcano-tectonic features. In fact, the dykes striking N80–100°E are parallel to the E-W trend of the pre-6 Ma spreading centre. The very few dykes striking N100–130°E can be considered consistent with the orientation of the Quaternary WNW-ESE en-echelon fissures of the Snaefellsnes Peninsula. Finally, the N50–80°E dykes are not parallel to any Plio-Quaternary structure of the Snaefellsnes peninsula. However, considering the work of Saemundsson (1979) that indicates an ENE trend for the pre-6 Ma Snaefellsnes rift, and the numerous ENE-striking dykes and normal faults cropping out along the coast northwards around Breidafjörður (Gudmundsson et al. 1996), we regard the

N50–80°E dykes in the study area to be coherent with the abovementioned, ENE-striking regional features.

From a petro-chemical point of view, dykes belong to two groups (basic and acid, respectively) of the alkaline series. This is consistent with the structural findings that suggest a complex history of multiple dyke intrusions in this area. The TAS diagram (Fig. 9a) shows a wide variety of rocks belonging to the same series: this is coherent with the field data where the dyke location suggests that some dykes represent the plumbing system allowing vertical upward magma escape from the laccolith-shaped magma chambers now exposed as the Lysuskard and Midhyrna intrusive bodies.

Inclined sheets

The 384 inclined sheets we measured have consistent dip directions in the western and eastern parts of the study area, whereas in the central area the sheets cross-cut each other with opposing dip directions (Fig. 5f). Sheets have been traced out to both sides of the study area until they disappear. For a better reconstruction of the inclined sheet geometry, we provide a 3D model considering all the measured sheets and computed the zones where they focus (Fig. 10). By considering the distribution of the dip directions, it is possible to confirm the

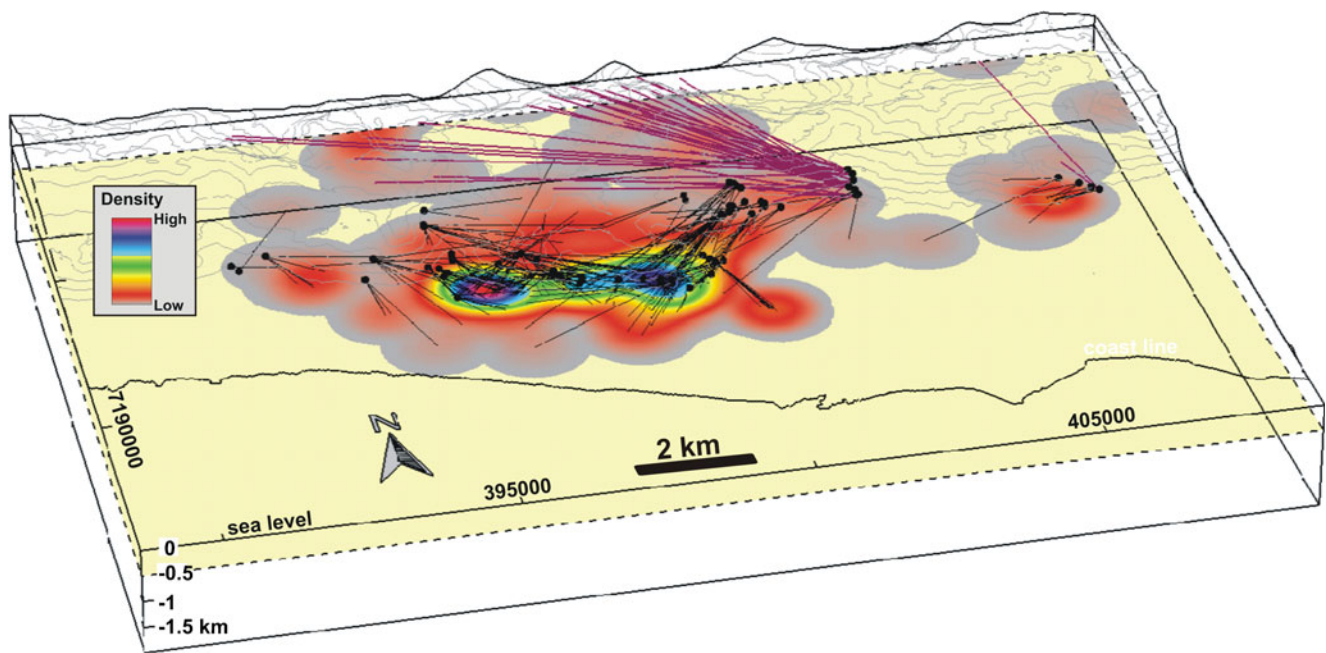


Fig. 10 Plot of the attitude of the inclined sheets downward in a three-dimensional view, suggesting the most likely location of the upper surface of the magma chambers from which sheets originated. Note that sheets

highlighted in black focus in two main areas, whereas a third population (*violet lines*) point towards a centre located further north, out of the studied zone

presence of two main systems of sheets with dip directions converging toward two focal areas and defining centrally inclined sheet swarms (Figs. 6, 7, 8, 9 and 10). The exception is represented by southward-dipping sheets that are missing: this can be easily explained by the distribution of cliffs and the exposure level, both factors that hinder the northern side of the centrally inclined sheet swarms from cropping out. Our data indicate that the sheets dipping to the E in the western part and the ones dipping to the W in the central part of the study area define one centrally dipping sheet swarm. Similarly, those sheets dipping E in the central part of the area, and to the W in the eastern part, can be attributed to another centrally dipping sheet swarm. The presence of two distinct sheet swarms is also confirmed by their cross-cutting relationships. Although these have been observed in only a few localities they show consistent results with the sheets belonging to the eastern centrally inclined sheet swarm offsetting those of the western swarm (Fig. 7b and c). This indicates the eastern swarm is younger. This 3D model suggests also the presence of a third possible centrally inclined sheet swarm with a focus located further north (*violet lines* in Fig. 10). The occurrence of multiple cone sheets is also consistent with the petrochemical analyses that indicate the presence of inclined sheets belonging to three main groups of basic, intermediate and acid composition, all of them belonging to alkaline series (Fig. 9a). The location and dip of the inclined sheets with different petro-chemical features is consistent with the field structural data indicating that most of the sheets propagated from hidden and deeper magma chambers, while a few should belong to the Lysuskard and Midhyrna intrusive bodies (Fig. 9b).

With regard to the mechanism of emplacement of these centrally dipping sheet swarms, we note there is no evidence of caldera development in the study area, and hence they cannot be interpreted in terms of the Phillip's (1974) model that suggests cone sheets injection in response to down-sagging of a caldera block providing space for tabular intrusions (Fig. 1a–b). We also do not favour the hypothesis that the inclined sheets might represent laterally propagating regional dykes, sourced from laterally adjacent magmatic systems, which are deflected around a central complex by stress field interference (Magee et al. 2012). Although this might be a valid interpretation in other situations, here the volume of magma emplaced in the two centrally inclined sheet swarms is much larger than the volume of magma emplaced in the surrounding area along the regional dykes. In fact, if we compare the total thickness of regional dykes and inclined sheets in a N-S section (that is perpendicular to the regional dykes), we obtain 29.9 and 64.3 m, respectively. This is a conservative estimate since we measured only the inclined sheets with the same strike of the regional dykes (N50–130°E). If we compare in fact the entire population of dykes and sheets (39.9 vs. 240.7 m) the difference is considerably greater. This difference in magma volumes implies that they have different sources and genesis, a conclusion consistent with preliminary geochemical analyses that suggest a compositional evolution of the magma.

In our opinion, the most viable hypothesis is that the two main centrally dipping sheet swarms are linked to two shallow magma chambers, in a similar way to previous findings, for example by Gudmundsson (1998), Klausen (2004) and

Tibaldi et al. (2008). These swarms are considered to be the expression of magmatic stresses induced by overpressure in the magma chamber that prevail over regional tectonic stresses. Conditions for magma flow from the chamber into the surrounding rocks are provided by lithostatic pressure plus magmatic pressure, which must exceed horizontal compressive stress in the roof of the chamber, perpendicular to the sheet, plus the tensile strength of the roof rock (Gudmundsson 1995). Sheets tend to intrude along planes containing σ_1 and σ_2 , and thus the force necessary for intrusion must overcome σ_3 plus the rock tensile strength. The excess pressure of the magma chamber creates a local compressive stress field around the reservoir, with trajectories of σ_1 arranged radially in the case of a spherical magma chamber, which is suitable for the intrusion of radial sheets as in Fig. 1c (Gudmundsson 1998). The trajectories of the σ_1 – σ_2 planes, and thus of the intrusive sheets, might vary depending on different shapes of the magma chamber and the presence of layering in the host rock with different Young's moduli. A sill-like magma chamber should produce centrally inclined sheets with a dip that does not change sensibly with distance from the centre of the sheet swarm (Fig. 1d) (Gudmundsson 1998; Schirnick et al. 1999; Bistacchi et al. 2012). With regard to layering, if the host rock is heterogeneous and highly anisotropic the orientation of sheets may be strongly affected (Gudmundsson and Brenner, 2004, 2005). Compared to other cases, such as the Esja Peninsula in Iceland where centrally inclined sheets were emplaced preferentially within almost isotropic hyaloclastite deposits (Pasquarè and Tibaldi 2007; Tibaldi and Pasquarè 2008), the host rock in the Midhyrna-Lysuskard area is composed of a succession of lava flows, suggesting a strong layering. However, the basaltic flows here tend to be massive, with only thin and localised autoclastic breccia interbeds. Although this succession can be considered to have anisotropies, it is made by dominant lava flows of basaltic type with only very local presence of thin layers of autoclastic breccias. We therefore believe that this succession is not affected by important differences in the Young's moduli. This is also true for the part of the study area where the inclined sheets intrude the massive gabbroic laccolith. Hence, we regard the geometry of the centrally inclined sheets as possibly reflecting the shape of the magma chamber.

In section view, the centrally inclined sheet swarms are not characterised by any systematic change of sheet dip with distance from the swarm centre. Above the central part of each swarm, inclined sheets are present but no vertical sheets have been found. The very few dykes in fact protruded from the Lysuskard and Midhyrna laccoliths. The only changes with distance are represented by the presence of steeper sheets (50–68°) limited up to 5.7 km from the focal area. Although this geometry is not very common, other cases of centrally inclined sheets whose dip does not change systematically with distance have been found elsewhere, for instance at the Tejada Complex on Gran Canaria (Canary Islands) by Schirnick et al.

(1999) and at the Cuillin Complex in the Island of Skye (Tibaldi et al. 2011). Concentricity and non-systematic dip variation of the cone sheets at the Cuillin Complex, on Gran Canaria and in the studied area in Iceland indicate that these swarms consist of a stack of parallel and sub-parallel intrusive sheets, as opposed to convergence towards a single point-like focus. In agreement with Schirnick et al. (1999), we believe that this geometry may result from lateral expansion and contraction of a shallow laccolith-like magma chamber; this might lead to sheet cone geometries with variable diameters through time. The sheet swarm geometry is thus not affected by regional stresses and strongly reflects the stress induced by the magma chamber. The lack of steeply dipping sheets at distances of 5–6 km from the swarm centre may be the result of the geometry of the chamber's lateral termination.

The data described above imply that the most plausible shape for the magma chamber and the surrounding intrusions might be the one portrayed in Fig. 1d, for reservoirs located at a depth of about 400 m below sea level for the western magma chamber and 500 b.s.l. for the eastern chamber (Fig. 10). Based on analogy with stratovolcanoes in Iceland today, whose top is generally at about 1,500–1,600 m above sea level, our estimate would indicate a magma chamber at about 2 km from the top of the volcano, at the time it was active. This compares very well with the estimated depth of the active magma chambers beneath Katla, Askja and Grimsvotn (Brown et al. 1991; Gudmundsson 1997, 2006; Sturkell et al. 2003; 2006).

Tectonic influence

The condition for sheet intrusion from an over-pressured magma chamber is more easily reached when tensile stress in the roof rock occurs, at least in part, through extensional tectonics produced by plate movements. In the Snaefellsnes Peninsula existing data do not suggest the presence of tectonic rift extension after 6 Ma (Jóhannesson 1980; Kristjánsson and Jonsson 1998; Martin and Sigmarsson 2010) related to horizontal σ_3 and σ_2 . The only hypothesis for Quaternary tectonic structures along the peninsula was proposed by Sigurdsson (1970), who invoked the presence of a major, although hidden, E-striking right-lateral strike-slip fault. This fault was thought to have been produced by differential spreading rates in north and south Iceland in late Pleistocene times. This hypothesis, suggesting horizontal σ_3 and σ_1 , is consistent with the N80–100°E and N100–130°E strike of the regional dykes mapped in the present study, with the late Quaternary eruptive fissures, and the alignment and elongation of pyroclastic cones. The N80–100°E strike we believe represents the emplacement of magma directly following the main transcurrent fault plane, as observed for example at the Esja Peninsula (Pasquarè and Tibaldi 2007; Tibaldi and Pasquarè 2008) and elsewhere (e.g. Tibaldi and Romero 2000; Tibaldi et al. 2010, and references therein). The N100–130°E strike may

correspond to magma emplacement along fracture planes of Riedel type normal to σ_3 , following the classical simple-shear scheme (Tchalenko 1970). The dykes striking N50–80°E may represent an orientation that has been previously found only in the north of the Snaefellsnes Peninsula (Gudmundsson et al. 1996). Magma is usually emplaced along planes that are suitably orientated with respect to σ_3 . Based on the different orientations of dykes found in the pre-Holocene rocks, in comparison to the trend of the Holocene eruptive fissures and aligned and elongated pyroclastic cones, we conclude that in the study area rotations of σ_3 have occurred during late Tertiary–Quaternary times. This suggestion may be supported by the occurrence of dykes with apparently different ages, as testified by dykes that pre-date and post-date the cone sheet swarms. The N50–80°E dykes may be older, in agreement with the trend of the Snaefellsnes paleo-rift, and as suggested by Saemundsson (1979) and Gudmundsson et al. (1996). Subsequently, the N80–130°E dykes were emplaced, following the development of the E–W right-lateral shear zone across the Snaefellsnes peninsula suggested by Sigurdsson (1970). The frequent WSW–ENE, W–E and WNW–ESE vertical fractures found in the same area are consistent with a changing stress field characterised by NNW–SSE, N–S and NNE–SSW trending σ_3 .

Turning to the few E–W- to WNW–ESE-striking dykes that offset the centrally dipping sheets, we suggest that these regional dykes were emplaced when the two local sub-surface magmatic systems were no more active. When the compressive stress field around the magma chamber produced by magma excess pressure weakens or disappears as it freezes, the effect of the regional tectonic stress field plays a decisive role in the injection of dykes. By comparison, in the case of an over-pressured magma chamber, local magma forces dominate the regional stress field. Thus, the distribution and geometry of intrusive sheets represent the changes in time and space of local magma forces vs. tectonic regional forces. This interpretation is also consistent with the presence of pervasive, shallow-dipping, fracture planes (Fig. 8) that mimic the attitude of the two centrally inclined sheet swarms, and with their decrease in frequency with distance from the centrally inclined sheet swarms. In the study area, the presence of both the inclined sheets and centrally dipping fracture swarms may be interpreted as originating by excess pressure from local magma reservoirs. Excess pressure diminishes with distance, explaining the more frequent dykes found in the areas surrounding the centrally inclined sheet swarms.

Conclusions

- For the first time, detailed measurements of dykes and inclined sheets have been carried out in the Snaefellsnes peninsula, showing a more complex picture than that depicted by the WNW–ESE en-echelon trend of the volcanic structures at the surface.

- Vertical dykes dominantly strike in the range N50–100°E, but also other orientations are present in the N100–130°E range and around N–S, with decreasing frequency.
- The N80–100°E-striking dykes are consistent with the regional E-striking, right-lateral strike-slip fault suggested by Sigurdsson (1970). The N100–130°E-striking dyke emplacement may have been guided by Riedel shear planes perpendicular to σ_3 , whereas the N50–80°E-striking dykes are parallel to the dyke population found on the northern side of the peninsula around Breidafjörður by Gudmundsson et al. (1996), as well as to the ENE trend of the pre-6 Ma Snaefellsnes rift documented by Saemundsson (1979).
- The inclined sheets have dip directions and dips consistent with the presence of two main centrally inclined sheet swarms; the sheets converge towards two ENE-aligned central areas, similarly to those found on the Esja Peninsula, where three aligned centrally inclined sheet swarms were documented (Tibaldi and Pasquaré 2008). Some inclined sheets should instead belong to another centre located further north of the studied area. Finally, few inclined sheets have been protruded from the Lysuskard and Midhyma intrusive bodies.
- The origin of the two main centrally inclined sheet swarms can be ascribed to magmatic over-pressure of two shallow magma chambers with a lobate shape, located at a possible depth of about 400–500 m b.s.l.
- The localized presence of these two centrally inclined sheet swarms, and of a similar system of centrally inclined fracture swarms that gradually disappear with distance from central focal areas, indicate causative stresses associated with a local magma source with an excess pressure greater than the regional tectonic stress field.
- The presence of vertical fractures orientated W–E, WSW–ENE and WNW–ESE also suggests the study area was affected by a changing stress regime producing different σ_3 trends consistent with the tectonic framework outlined above.

Acknowledgements This is a contribution to the International Lithosphere Program Task Force II “Volcanoes and society: environment, health and hazards”. The Authors are grateful to Andrea Villan, Luca Corti and Luca Fumagalli for field cooperation. Claudia Corazzato is acknowledged for her insights and comments to the 3D structural model. Agust Gudmundsson and an anonymous reviewer are acknowledged for their insightful comments and suggestions to the previous version of the manuscript.

References

- Acocella V, Neri M (2009) Dike propagation in volcanic edifices: overview and possible developments. *Tectonophysics* 471:67–77

- Ancochea E, Brandle JL, Huertas MJ, Cubas CR, Hernan F (2003) The felsic dikes of La Gomera (Canary Islands): identification of cone-sheet and radial dyke swarms. *J Volcanol Geotherm Res* 120:197–206
- Bailey EB, Clough CT, Wright WB, Richey JE, Wilson GV (1924) The Tertiary and post-Tertiary geology of Mull, Loch Aline and Oban. Geological Survey of Scotland Memoir, 445 p
- Bald N, Noe-Nygaard A, Pedersen K (1971) The Krokksfjordur central volcano in North-West Iceland. *Acta Naturalia Islandica*, II, 10, 29 pages.
- Bistacchi A, Tibaldi A, Pasquarè FA, Rust D (2012) The association of cone-sheets and radial dykes: data from the Isle of Skye (UK), numerical modelling, and implications for shallow magma chambers. *Earth Planet Sci Lett* 339–340:46–56
- Bonali FL, Corazzato C, Tibaldi A (2011) Identifying rift zones on volcanoes: an example from La Réunion Island. *Indian Ocean B Volcanol* 73(3):347–366. doi:10.1007/s00445-010-0416-1
- Brown GC, Everett SP, Rymer H, McGarvie DW, Foster I (1991) New light on caldera evolution—Askja, Iceland. *Geology* 19:352–355
- Burchardt S, Tanner DC, Troll VR, Krumbholz M, Gustafsson LE (2011) Three-dimensional geometry of concentric intrusive sheet swarms in the Geitafell and the Dyrjöll volcanoes, eastern Iceland. *Geochemistry Geophy Geosy* 12:Q0AB09, doi: 10.1029/2011GC003527.
- Chadwick WW Jr, Dieterich JH (1995) Mechanical modelling of circumferential and radial dike intrusion on Galapagos volcanoes. *J Volcanol Geotherm Res* 66:37–52
- Corazzato C, Tibaldi A (2006) Fracture control on type, morphology and distribution of parasitic volcanic cones: An example from Mt. Etna, Italy. *J Volcanol Geotherm Res* 158(1–2):177–194
- Cox KG, Bell JD, Pankhurst RJ (1979) The interpretation of igneous rocks. George Allen and Unwin, London
- Einarsson P (2008) Plate boundaries, rifts and transforms in Iceland. *Jökull* 58:35–58
- Einarsson P, Brandsdóttir B (1980) Seismological evidence for lateral magma intrusion during the July 1978 deflation of the Krafla volcano in NE Iceland. *J Geophys* 47:160–165
- Einarsson P, Brandsdóttir B, Gudmundsson MT, Björnsson H, Grönvold K, Sigmundsson F (1997) Center of the Iceland hotspot experiences volcanic unrest, *Eos Trans. AGU* 78:369374–369375
- Flude S, Burgess R, McGarvie DW (2008) Silicic volcanism at Ljósufjöll, Iceland: insights into evolution and eruptive history from Ar–Ar dating. *J Volcanol Geotherm Res* 169(3–4):154–175
- Fridleifsson IB (1977) Distribution of large basaltic intrusions in the Icelandic crust and the nature of the layer 2–layer 3 boundary. *Geol Soc Am Bull* 11:1689–1693
- Galland O, Planke S, Neumann E-R, Malthe-Sørensen A (2009) Experimental modelling of shallow magma emplacement: application to saucer-shaped intrusions. *Earth Planet Sci Lett* 277:373–383
- Gautneb H, Gudmundsson A (1992) Effect of local and regional stress fields on sheet emplacement in West Iceland. *J Volcanol Geotherm Res* 51:339–356
- Gautneb H, Gudmundsson A, Oskarsson N (1989) Structure, petrochemistry, and evolution of a sheet swarm in an Icelandic central volcano. *Geol Mag* 126:659–673
- Geikie A (1897) The ancient volcanoes of Great Britain. Macmillan, London
- Geshi N (2005) Structural development of dike swarms controlled by the change of magma supply rate: the cone sheets and parallel dike swarms of the Miocene Otoge igneous complex, Central Japan. *J Volcanol Geotherm Res* 141:267–281
- Gianelli G (1972) Cumulus textures of the Midhyrna layered intrusion, Snaefellsnes Peninsula, western Iceland. *Boll Soc Geol Ital* 91:419–438
- Gudmundsson A (1990) Emplacement of dikes, sills and crustal magma chambers at divergent plate boundaries. *Tectonophysics* 176(3–4): 257–275
- Gudmundsson A (1995) Infrastructure and mechanics of volcanic systems in Iceland. *J Volcanol Geotherm Res* 64:1–22
- Gudmundsson MT (1997) Gravity and magnetic studies of the subglacial Grímsvötn volcano, Iceland: implications for crustal and thermal structure. *J Geophys Res* 102(B4):7691–7704
- Gudmundsson A (1998) Magma chambers modeled as cavities explain the formation of rift zone central volcanoes and their eruption and intrusion statistics. *J Geophys Res* 103(B4):7401–7412
- Gudmundsson A (2000) Dynamics of volcanic systems in Iceland: example of tectonism and volcanism at juxtaposed hot spot and mid-ocean ridge systems. *Annu Rev Earth Planet Sci* 28:107–140
- Gudmundsson A (2002) Emplacement and arrest of sheets and dikes in central volcanoes. *J Volcanol Geotherm Res* 116:279–298
- Gudmundsson A (2006) How local stresses control magma-chamber ruptures, dyke injections, and eruptions in composite volcanoes. *Earth-Sci Rev* 79:1–31
- Gudmundsson A, Brenner SL (2004) How mechanical layering affects local stresses, unrests, and eruptions of volcanoes. *Geophys Res Lett* 31(16):L16606
- Gudmundsson A., Brenner SL (2005) On the conditions of sheet injections and eruptions in stratovolcanoes. *Bull Volcanol* 67:768–782
- Gudmundsson A, Bergerat F, Angelier J (1996) Off-rift and rift-zone palaeostresses in Northwest Iceland. *Tectonophysics* 255:211–228
- Jacoby W, Gudmundsson MT (2007) Hotspot Iceland: an introduction. *J Geodyn* 43(1):1–5
- Jakobsdóttir SS, Roberts MJ, Gudmundsson GB, Geirsson H, Slunga R (2008) Earthquake swarms at Upptýppingar, north-east Iceland: a sign of magma intrusion? *Stud Geophys Geod* 52(4):513–528
- Jóhannesson H (1980) Stratigraphy and the development of rift zones in West Iceland. *Náttúrufræðingurinn* 50:13–31 (in Icelandic)
- Johnson SE, Paterson SR, Tate MC (1999) Structure and emplacement history of a multiple-center, cone-sheet-bearing ring complex: the Zarza intrusive complex, Baja California, Mexico. *Geol Soc Am Bull* 111(4):607–619
- Kjartansson G (1968) Geological Map of Iceland. Sheet 2. Icelandic Museum of Natural History and Iceland Geodetic Survey, Reykjavik, scale 1:250,000.
- Klausen MB (2004) Geometry and mode of emplacement of the Thverartindur cone sheet swarm, SE Iceland. *J Volcanol Geotherm Res* 138:185–204
- Klausen MB (2006) Geometry and mode of emplacement of dike swarms around the Birnadalstindur igneous centre, SE Iceland. *J Volcanol Geotherm Res* 151(4):340–356
- Kristjánsson L, Jónsson G (1998) Aeromagnetic results and the presence of an extinct rift zone in western Iceland. *J Geodyn* 25(1–2):99–108
- Magee C, Stevenson C, O'Driscoll B, Schofield N, McDermott K (2012) An alternative emplacement model for the classic Ardnamurchan cone sheet swarm, NW Scotland, involving lateral magma supply via regional dykes. *J Struct Geol* 43:73–91
- Martin E, Sigmundsson O (2010) Thirteen million years of silicic magma production in Iceland: links between petrogenesis and tectonic settings. *Lithos* 116:129–144
- Mathieu L, van Wyk de Vries B, Holohan EP, Troll VR (2008) Dykes, cups, saucers and sills: analogue experiments on magma intrusion into brittle rocks. *Earth Planet Sci Lett* 271:1–13
- Mjelde R, Raum T, Breivik AJ, Faleide JJ (2008) Crustal transect across the North Atlantic. *Mar Geophys Res* 29:73–87
- Moorbath S, Sigurdsson H, Goodwin R (1968) K-R ages of the oldest exposed rocks in Iceland. *Earth Planet Sci Lett* 4(3):197–205
- Paquet F, Dauteuil O, Hallot E, Moreau F (2007) Tectonics and magma dynamics coupling in a dyke swarm of Iceland. *J Struct Geol* 29: 1477–1493
- Pasquarè F, Tibaldi A (2007) Structure of a sheet-laccolith system revealing the interplay between tectonic and magma stresses at Stardalur Volcano, Iceland. *J Volcanol Geotherm Res* 161(1–2):131–150
- Phillips WJ (1974) The dynamic emplacement of cone sheets. *Tectonophysics* 24:69–84
- Saemundsson K (1979) Outline of the geology of Iceland. *Jökull* 29:7–28

- Schilling JG (1973) Iceland Mantle Plume: Geochemical Study of Reykjanes Ridge. *Nature* 242(5400):565–571
- Schirnack C, van den Bogaard P, Schmincke H-U (1999) Cone sheet formation and intrusive growth of an oceanic island—the Miocene Tejada complex on Gran Canaria (Canary Islands). *Geology* 27(3):207–210
- Sigmundsson F, Schmundsson K (2008) Iceland: a window on North-Atlantic divergent plate tectonics and geologic processes. *Episodes* 31(1):92–97
- Sigurðsson H (1970) Structural origin and plate tectonics of the Snæfellsnes volcanic zone, Western Iceland. *Earth Planet Sci Lett* 10:129–135
- Siler DL, Karson JA (2009) Three-dimensional structure of inclined sheet swarms: implications for crustal thickening and subsidence in the volcanic rift zones of Iceland. *J Volcanol Geotherm Res* 18(8):333–346
- Steinþorsson S (1967) Tvær nýjar C14 aldurákvarðanir á öskulögum úr Snæfellsjökli (Two new C14 dates on tephra layers from Snæfellsjökull). *Náttúrufræðingurinn*
- Sturkell E, Einarsson P, Sigmundsson F, Hreinsdóttir S, Geirsson H (2003) Deformation of Grímsvötn volcano, Iceland: 1998 eruption and subsequent inflation. *Geophys Res Lett* 30:B4
- Sturkell E, Einarsson P, Roberts MJ, Geirsson H, Gudmundsson MT, Sigmundsson F, Pinel V, Gudmundsson GB, Ólafsson H, Stefánsson R (2008) Seismic and geodetic insights into magma accumulation at Katla subglacial volcano, Iceland: 1999 to 2005. *J Geophys Res* 113:B3
- Tchalenko JS (1970) Similarities between shear zones of different magnitudes. *Geol Soc Am Bull* 81(6):1625–1640
- Tentler T, Temperley S (2007) Magmatic fissures and their systems in Iceland: a tectonomagmatic model. *Tectonics* 26, TC5019. doi:10.1029/2006TC002037
- Thordarson T, Hoskuldsson A (2002) *Classic Geology in Europe*. Monograph, VIII, pp 200
- Tibaldi A (1995) Morphology of pyroclastic cones and tectonics. *J Geophys Res* 100(12):24521–24535
- Tibaldi A, Romero JL (2000) Morphometry of Late Pleistocene–Holocene faulting in the southern Andes of Colombia and volcano-tectonic relationships. *Tectonics* 19(2):358–377
- Tibaldi A, Pasquaré FA (2008) A new mode of inner volcano growth: the “flower intrusive structure”. *Earth Planet Sci Lett* 271:202–208
- Tibaldi A, Pasquaré FA, Tormey D (2010) Volcanism in reverse and strike-slip fault settings. In: *New frontiers in integrated solid earth sciences*, Editors: Cloetingh S, Negendank J, Springer, New York, 315–348. doi: 10.1007/978-90-481-2737-5
- Tibaldi A, Pasquaré AF, Rust D (2011) New insights into the cone sheet structure of the Cuillin Complex, Isle of Skye, Scotland. *J Geol Soc Lond* 168:689–704
- Upton BGJ, Wright JB (1961) Intrusions of gabbro and granophire in the Snæfellsness, western Iceland. *Geol Mag* 98(6):488–492
- Walker GPL (1958) Geology of the Reydarfjordur Area, Eastern Iceland. *Q J Geol Soc* 114(1/4):367–391
- Walker GPL (1960) Zeolite zones and dike distribution in relation to the structure of the basalts of eastern Iceland. *J Geol* 68:515–528
- Walker GPL (1974) The structure of Eastern Iceland. In: Kristjánsson L (ed) *Geodynamics of Iceland and the North Atlantic Area*. Reidel, Dordrecht, pp 177–188
- Walker GPL (1975) Intrusive sheet swarms and the identity of Crustal Layer 3 in Iceland. *J Geol Soc Lond* 131:143–161
- Walker GPL (1992) “Coherent intrusion complexes” in large basaltic volcanoes — a new structural model. *J Volcanol Geotherm* 50(1–2):41–54
- Walker GPL (1999) Volcanic rift zones and their intrusion swarms. *J Volcanol Geotherm* 94(1–4):21–34
- Welke H, Moorbath S, Cumming GL, Sigurdsson H (1968) Lead isotope studies on igneous rocks from Iceland. *Earth Planet Sci Lett* 4(3):221–231
- Wilson M (1989) *Igneous petrogenesis*. Unwin Hyman, London